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COMPUTATIONAL FLUID DYNAMICS AS A TOOL FOR INVESTIGATING SEPARATED FLOW IN RIVER BENDS

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ABSTRACT

The detailed three-dimensional structure of the flow patterns in river bends with separated flow and factors controlling the existence and characteristics of these flow patterns are unclear at present. It is shown here, firstly, how a computational fluid dynamics (CFD) program may be used to reproduce the qualitative features of the mean flow in a real river bend to allow testing of the model's capabilities. It is then shown how the CFD code may be used to construct hypothetical channel bends which allow the experimentation necessary to investigate the controls on the extent of the separated flow.

KEY WORDS numerical modelling; flow separation; meandering rivers

INTRODUCTION

Computational fluid dynamics (CFD) software allows calculation of the detailed two- or three-dimensional spatial pattern of fluid flow variables through user-defined flow geometries. This paper illustrates how such software can be used to describe the mean flow patterns present in river bends with separated flow and to conduct experiments which aim to investigate the origins of these flow patterns. Flow separation at the concave bank of sharply curving river bends and the region of gently circulating flow that develops there has long been recognized as a site of fine-grained deposition leading to the development of concave bank benches (e.g. Hickin, 1986; Page and Nanson, 1982). However, the detailed structure of the flow in such bends and the factors controlling the characteristics of the separated flow region remain unclear.

The basis of the approach proposed here is to use the CFD code in an experimental capacity to investigate these controls. Firstly, however, the CFD code must be applied to natural flow geometries to test its predictions against field measurements and to validate the set-up used in the experiments. The experimental approach involves setting up the hypothetical geometry of a river bend of interest and using the CFD program to simulate the three-dimensional mean flow patterns present, given appropriate boundary conditions. Then, by varying systematically aspects of the channel geometry, it is possible to investigate the factors determining the existence and nature of the separated flow.

A number of CFD programs are available commercially, although the work reported here uses the CFD code *FLUENT* (version 4.2) (Fluent Inc., 1993a, b), which was available at the University of Sheffield.

BASIS OF FLUENT

FLUENT calculates flow properties at points in a fluid by dividing the fluid domain through a geometry of interest into a three-dimensional grid of six-sided volumes and solving the Reynolds averaged Navier–Stokes equations for each individual cell. The geometry and grid generation is completed initially in a separate pre-processing program (*PreBFC*; Fluent Inc., 1993b) and this information is then input to *FLUENT* for model set-up and running. The physical properties of the fluid are defined and conditions

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at the boundaries of the fluid domain are specified, such as the flow inputs, outlet planes, and wall type and roughness. The governing equations are integrated about each control volume to yield algebraic equations which are then solved numerically to give values for flow variables for each cell. *FLUENT* solves all the equations for each cell sequentially using an iterative solution procedure which continues until all equations are satisfied at all points.

It is not feasible to directly simulate all turbulent motions in the flow because this would require an extremely fine grid and very short time steps in the calculation, which would give rise to impractical computational requirements. To resolve this problem, models have been developed which account for the influence of turbulent momentum transfer on the mean flow properties. Three turbulence models are available in *FLUENT*: a standard κ–ϵ model, a Reynolds stress model and an *RNG* κ–ϵ model. Recommendations as to the types of situations for which each of these models is appropriate are given in the *FLUENT* manual (Fluent Inc., 1993a). The detailed theory of such turbulence models and solution procedures are described elsewhere (e.g. Nezu and Nakagawa, 1993; Demuren, 1993; Fluent Inc., 1993a) and so there is no need to reproduce the information here.

FLUENT allows the specification of rough boundaries indirectly by modelling the effect of the rough boundary on the near-wall flow by means of a wall function, E', derived from the logarithmic law of the wall. The value of the wall function alters for different roughness and flow conditions and equations relating E' to the flow are given (see below). The value of E' can therefore be selected to approximate a required boundary roughness.

In the version of *FLUENT* used here (version 4.2), a water surface is modelled as a fixed lid on the flow with the fluid/wall interface defined as frictionless. This is achieved by making the computational fluid cells adjacent to the boundary independent of the boundary by cutting all computational links between fluid and wall cells. The boundary therefore defines no shear stress on the adjacent fluid and the wall becomes frictionless.

The rate at which a solution develops can be controlled to make it stable. At each iteration, solution of the equations yields revised values for all variables, but it is not usually possible to substitute these revised values directly into the equations to continue the calculation. Convergence is achieved by under-relaxation of the equations, which involves reducing the change produced in each variable during an iteration. Therefore the new values used to continue the calculation are the old values plus only a small part of the change computed last time the equations were solved. The under-relaxation parameter can be altered for each equation, therefore altering how much each variable is allowed to change every iteration, hence slowing or speeding the solution. Complicated problems may require small amounts of change initially in order to be stable, but can be speeded up once stability has been achieved.

Once all the equations are balanced at all points in the domain, the solution has converged. Iterations continue until this is achieved. To judge progress towards convergence, normalized residuals are calculated for each equation every iteration. Residuals are a measure of the imbalance in the equations throughout the flow field. A solution is well converged when the normalized residuals are reduced to the order of $1{\cdot}0 \times 10^{-3}$. Results from the calculations are available as graphical or numerical output for each cell, with the values of flow variables stored at the cell centres.

APPLICATION OF *FLUENT* TO RIVERS

Two approaches to modelling rivers are illustrated here. One is to use the surveyed bend geometry and water surface of real river bends and to measure the boundary roughness and inlet flow conditions necessary to set the model up. By comparing model output with field measurements, some idea of the reliability of model results can be gained. However, this approach does not easily lend itself to experimentation given that it is desirable to vary systematically bend properties. Any real river bend is likely to exhibit a combination of both characteristic bend features and site-specific details, so it is difficult to isolate the important causative features for the flow patterns present. Furthermore, modelling large numbers of real bends would require a considerable amount of surveying. Therefore it is proposed here that in order to allow systematic experimentation with bend characteristics, hypothetical river bends must be used, based on the flow

geometries of real rivers but with strictly controlled geometrical properties which allow for controlled changes.

DESCRIBING FLOW IN REAL RIVER BENDS

The flow geometry of real river bends can be set up and the flow modelled using *FLUENT*, and by testing the flow predictions against field measurements the capabilities of the model can be checked. In *PreBFC* a geometry is created by defining points in three-dimensional space which lie along the boundaries of the fluid and define its shape, joining the points together to create curves along the edges of the boundaries and then joining the curves together to create the boundary surfaces. Surface may be joined together to create further connecting surfaces.

The set-up of a real river bend requires surveying a series of cross-sections around the bend of interest. The data required are the form of the channel bed across the channel, and the position of the water surface along the bank edge. This information can then be used to create a series of cross-sectional planes through the fluid which are then joined together along the channel to create the necessary bed, banks and water surface. The cross-sections at each end of the channel define the inlet and outlet planes. Field measurements of the inlet flow field and bed roughness are also required.

The bend used to test this approach was a sharp right-hand bend on the River Dean, Cheshire, with a pronounced zone of recirculating flow at the inner bank and a noticeable narrow fast flow around the outer bank. The bend geometry consists of a shallow (20 cm deep) riffle entering the bend, which has a very deep pool and pronounced point bar.

The computational grid generated for this experiment consisted of 75 cells along the channel, eight cells through the flow depth and 30 cells across the channel, but with the cells concentrated to twice the normal density towards the outer bank to help resolve the narrow fast flow there. The non-uniform spacing of the grid cells across the channel can be seen in the plotting positions of the resultant velocities (Figure 1). The inlet flow distribution at the upstream end of the reach input to *FLUENT* was based on electromagnetic current meter (ECM) measurements at the entrance to the bend in the field, but with considerable interpolation both between measurement points and through the flow depth to fix inlet velocities for all the inlet flow cells. The law of the wall was fitted to the ECM data to describe the velocity profile at each measurement station and then the intervening flow was derived by linear interpolation. The 240 inlet flow cells were represented by 35 inlet regions, i.e. seven profiles of five velocities, so some averaging was necessary. The inlet flow distribution is therefore approximately correct.

Using the equations mentioned above, a value of E' for the channel bed in the shallow inlet region of the bend should be about 0·001, but it was found that the model would not run unless a smoother bed was specified ($E' = 0{\cdot}025$). Two-dimensional experiments, through the flow depth, showed that to allow for rough walls in shallow flow the computational cells near the bed must be relatively large, therefore reducing the possible resolution of the velocity profile. Therefore, correct specification of bed roughness in shallow flow is problematic and warrants further attention.

Detailed validation of the flow predictions made by *FLUENT* requires testing the predictions of the spatial flow patterns, the magnitudes of cross- and long-stream velocity components, and velocity vector magnitudes against field measurements. These tests have been conducted and are reported in Hodskinson and Ferguson (submitted). The results were encouraging, with the *FLUENT* code reproducing the qualitative features of the mean flow very well. Discrepancies existed in the quantitative comparisons; however, these are likely to be related to the problem of roughness specification mentioned above. Figure 1 illustrates how the flow patterns observed in the field are reproduced by *FLUENT*. Both model and field data show the flow converging strongly to the outer bank at the bend entrance, a narrow decelerating fast flow around the outer bank, a largely gently recirculating zone at the inner bank, and expanding flow downstream of the bend, with a region of noticeably diverging flow against the inner bank as part of the flow enters the recirculation zone. The comparison presented in Figure 1 and the test data reported in Hodskinson and Ferguson (submitted) give considerable confidence in the qualitative flow patterns generated by *FLUENT* where direct testing is not possible.

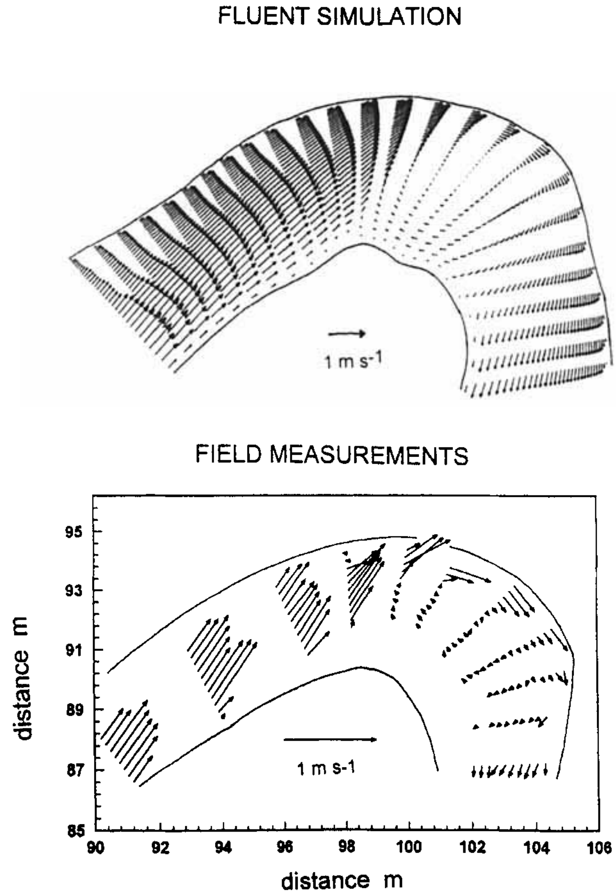

Figure 1. Comparison between the flow patterns calculated by *FLUENT* and the flow patterns measured in the field for a bend on the River Dean, Cheshire

EXPERIMENTING WITH HYPOTHETICAL RIVER BENDS

In a river, the water is bounded by four surfaces: a bed, two banks and the water surface. Therefore, a simplified flow geometry in a river may be defined by four curves: two specifying the line of the water surface along each bank and two specifying the base of each bank along the channel. Joining these curves across the top and bottom, down each side and across the ends of the channel creates the flow geometry necessary for model set-up. By varying the position of the bed under the water surface along each bank, a spatially varying bed topography can be created. A water surface slope can also be accommodated. The ends of the channel are defined as an inlet and outlet plane.

The hypothetical bends illustrated here are based on a reach of a small upland stream with channel slope of 0·001. Data for the channel slope and corresponding grain size characteristics are available for the Allt Dubhaig (Ferguson and Ashworth, 1991) and these were used to estimate plausible boundary conditions for the model. The channel is modelled at bankfull discharge and has a slope of 0·001, with the straight reaches being taken as 8 m wide and 0·6 m deep. Pools deepen to 1·5 m and bars shallow to 0·1 m. A value of 0·02 m was used for the median grain size of the bed, based on a surface count (Ferguson and Ashworth, 1991). The centre-line water surface slope in the model is uniform along the channel at a value of 0·001, with zero cross-channel slope.

There is some evidence for justifying a uniform centre-line water surface slope. Leopold *et al.* (1964) demonstrate that in meandering channels the water surface slope along the channel can be uniform at

bankfull, although this was not the case for straight reaches, and Carling (1991) demonstrates that along a reach of the River Severn the local energy slopes, in both pools and riffles, converged at bankfull discharge to a slope similar to the regional slope of the reach. The lack of a cross-channel water surface slope in the model is not strictly correct, as superelevation would be expected in the bends. However, Hodskinson and Ferguson (submitted) demonstrate that the velocity predictions made in the test bend on the River Dean (referred to above), using the correct, surveyed water surface, were almost identical to the predictions made using a cross-sectionally flattened water surface. In addition to this test, the predictions of the hypothetical experiments appear correct. Helical flow in bends is thought to be due to superelevation of the water surface against the outer bank, and flow separation, and the associated flow reversal, is thought to be caused by local adverse pressure gradients in the flow forcing it upstream, e.g. a reversing of the normal downstream surface slope (Markham and Thorne, 1992; Ippen and Drinker, 1962). The ability of the *FLUENT* model to generate both plausible helical flow and flow separation (see Figure 2), despite there being a uniform downstream water surface

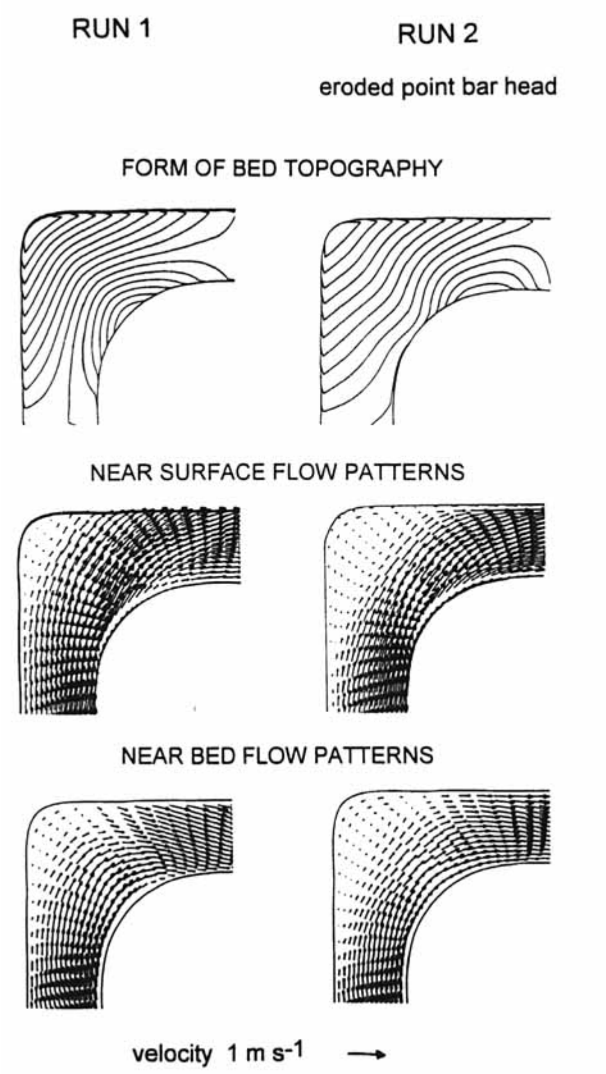

Figure 2. Results of a hypothetical bend experiment in which the point bar head was eroded. Only the flow patterns in the actual experimental bend are shown

slope and no cross-channel variation, suggests that this water surface detail is not strictly necessary for reproducing the qualitative flow features of bends with this model.

The water within the flow geometry was divided into a computational grid of 105 cells along the channel, five cells through the flow depth and 30 cells across the channel. This distribution of cells is fitted to the shape of the geometry so that where the channel widens and deepens cell dimensions increase, but where the channel narrows and shallows cell dimensions decrease. Therefore, whilst the cells are evenly distributed they are not of uniform dimensions.

Apart from the geometry and computational grid, the model requires the specification of boundary roughness and a velocity field at the entrance to the channel. The water surface is defined as frictionless, as described above. Boundary roughness and the inlet flow velocity were estimated as follows.

The Darcy–Wisebach friction factor *ff* was computed for the straight uniform channel using the empirical relation of Knighton (1984), taking D_{84} as $2D_{50}$

$$\frac{1}{ff} = 0{\cdot}82 \ln\left(4{\cdot}3\frac{R}{D_{84}}\right) \tag{1}$$

where R is the hydraulic radius of the straight reach, and a value for the mean channel velocity was then determined as:

$$v = \frac{8gRS}{ff} \tag{2}$$

where S is the channel slope. For a value of D_{84} of 0·04 m, a mean inlet flow velocity of 0·668 m s^{-1} was calculated. This was specified as the inlet flow across the whole cross-section at the upstream end of the model reach to avoid having to estimate the cross-channel velocity distribution. A length of channel of approximately 30 m was added to the model upstream of the bend of interest to allow the flow to adjust to the channel geometry and establish a realistic velocity profile and cross-channel asymmetry before entering the bend under investigation. In the experiment illustrated in Figure 2, the inlet channel was a curved reach of opposite curvature to the bend under investigation. This followed the pattern of a field site on the Allt Dubhaig in which a left-hand bend entered a very sharply curving right-hand bend which exhibited outer bank flow separation and a concave bank bench.

The wall function E', representing the effect of boundary roughness on the flow, is defined as:

$$E' = \frac{E}{1 + 0{\cdot}3ks^{+}} \tag{3}$$

where E is the value of E' for a smooth wall (9·8), and ks^{+} is defined as:

$$ks^{+} = \frac{\rho ksu^{*}}{\mu} \tag{4}$$

where ρ and μ are the density and dynamic viscosity of water, respectively, and ks (the effective roughness height) can be related to bed grain size (Bray, 1982; Ferguson, 1986) as $ks = 3{\cdot}5D_{84}$ and the shear velocity u^{*} is given by:

$$u^{*} = gRS \tag{5}$$

With D_{84} taken as 0·04 m, a value for E' of 0·00424 was obtained. This was applied uniformly over the whole bed as no information was available regarding the grain size variation through bends. Many point bars on the Allt Dubhaig are gravelly, so this is a reasonable first approximation. Similarly, no information was available as to the roughness of the channel banks. A value of E' of 0·01 was set for both banks. Using the equations above, this equates to a D_{50} of 3·9 mm. Therefore the channel banks were defined as not smooth but considerably less rough than the channel bed.

The *RNG*κ–ϵ turbulence model was selected, as this is recommended by Fluent Inc. (1993a) for flows which separate, have high streamline curvature and are strained by stagnation. The *FLUENT* manual presents data detailing the superior predictions of the *RNG*κ–ϵ model over the standard turbulence model

for separated flows. The density of water was set at $1000 \mathrm{kg\,m^{-3}}$, with a dynamic viscosity of $0{\cdot}0013 \mathrm{kg\,m^{-1}\,s^{-1}}$. Using the set-up described and default under-relaxation parameters, most hypothetical experiments reached a converged solution after approximately 700 iterations. Some experiments, however, required the under-relaxation parameters to be reduced initially in order to stabilize the calculation. Such experiments took around 1500 iterations to converge. Figure 2 shows the type of hypothetical experiment conducted and the output obtained. The experiment shows the effect that eroding the point bar head can have on the distribution of flow through a bend, and on the extent of the outer bank separated region, whilst the planform remains unchanged. When the point bar head is eroded, the distribution of flow in the bend changes and the separated region at the outer bank grows in extent. Erosion of the bar head was achieved simply by altering the elevation of the base of the right bank of the channel around the upstream part of the bend. Note the deviation between surface and bed of the velocity vectors in each bend, indicating helical flow. A series of such hypothetical experiments are presented in Hodskinson and Ferguson (submitted), along with a full discussion of the geomorphological implications of the results.

DISCUSSION

It has been shown how the computational fluid dynamics program *FLUENT* may be used to conduct experiments into the nature of separated flow in river bends by defining plausible hypothetical channel bends and varying aspects of the channel geometry to see the effects. It has also been shown that the model is capable of reproducing qualitatively correct flow patterns observed in natural channels. Using computational fluid dynamics in an experimental way may suggest important controls on flow properties, evidence for which may then be sought in the field. Such a combination of studies may shed considerable light on the factors influencing flow characteristics in bends, as well as being applicable to other situations, e.g. braid confluences. However, an important area of uncertainty requires further clarification, i.e. the ability to specify realistic bed roughness in all situations. Other refinements of the approach may be the specification of spatially variable bed and bank roughness and investigation of the sensitivity of flow patterns to this. Despite these imperfections, it is argued that the hypothetical approach described here may yield important insights into the origins and characteristics of separated flow patterns in river bends.

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